# *Neutronics Design and Analysis of the 50 MWe Novel Modular BWR (NMR-50) with Multi-physics Simulation Code System*


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# *Outline of the Talk*

- Introduction
- Design Tasks in the First Phase
- The NMR-50 Core Modeling
  – CASMO/PARCS/RELAP5 Code System
- Fuel Assembly Design and Analysis
- Core Simulation and Performance
- Summary

# *Introduction of the NMR-50*

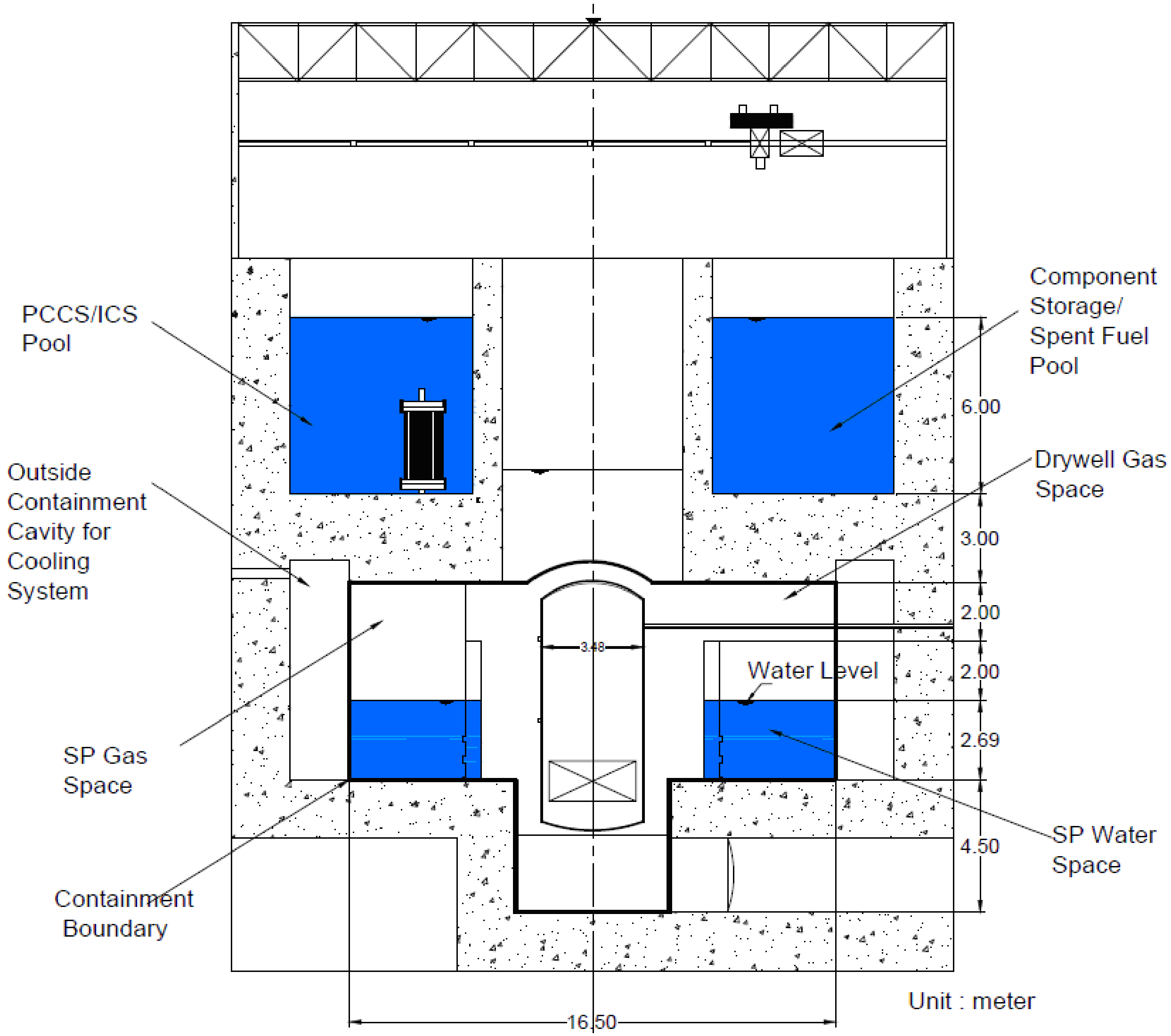
- NMR-50 is a small modular reactor design featuring with latest BWR safety technologies.
- Research labs at Purdue University take the leading role of the NMR-50 development.
- NMR-50 is an improved design which is originally down scaled from GE 600 MWe SBWR.
- Logical path to accomplish NMR-50 may require scaling study, T/H design, neutronics analysis, safety analysis and experimental testing, etc.
- Natural circulation instability and transients are examples remained as challenges to passive safety regards in NMR-50.

# Small Modular Reactors (SMR)

- The size of the reactor unit is "small"
- Reactors can be deployed modularly

| Name | Vendor | Power (MWe) | Type |
|---|---|---|---|
| mPower | B&W | 125 | PWR |
| NuScale | NuScale | 45 | PWR |
| IRIS-50 | WESC | 50 | PWR |
| HPM(G4M) | LANL | 25 | LMFR |
| NMR-50 | Purdue | 50 | BWR |

# Schematic of the NMR-50




**Ref.** M. Ishii et al., “Double Passively Safe Novel Modular Reactor 50”, NUEP CFP Narrative 3493, (2012)

# *RPV designs of the NMR-50*

| SMR | | NMR-50 | NuScale | mPower |
|---|---|---|---|---|
| Type | | Simplified BWR | Integral PWR | Integral PWR |
| | | Two-phase natural circulation | Single phase Natural circulation | Forced circulation |
| Rating | | 50 MWe | 45 MWe | 125 MWe |
| Primary system pressure | | 7.171 MPa | 12.76 MPa | 14 MPa |
| Reactor vessel | Height | 8.5 m | 13.7 m | 23 m |
| | Diameter | 3.48 m | 2.7 m | 3.6 m |
| Refueling cycle | | 10 years | 2 years | 5 years |
| Enrichment | | <5% | <4.95% | 5% |

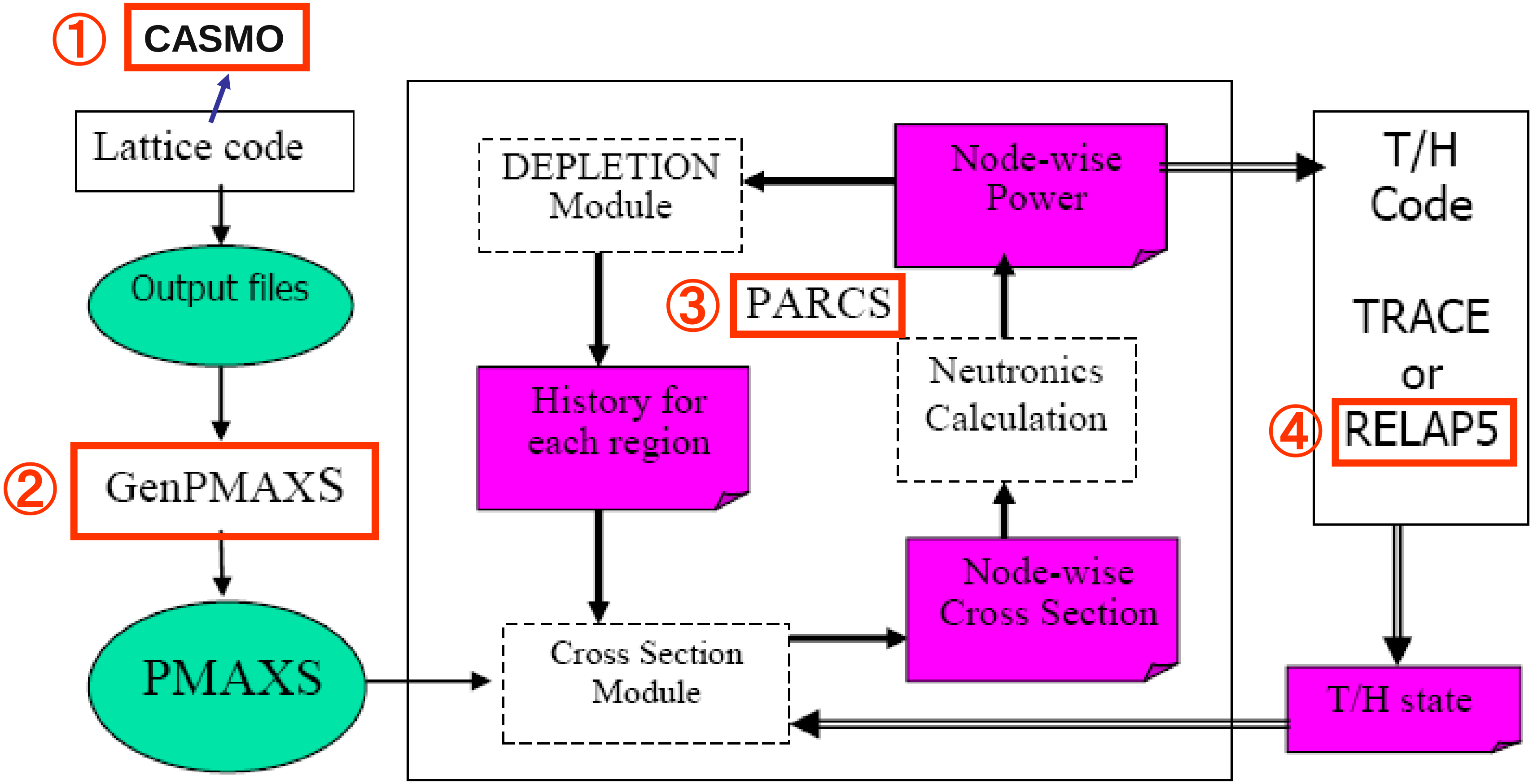
# *Advantageous Features of the NMR-50*

- Fully passive safety systems
- Two-phase natural circulation
- A compact and simplified design
- High energy conversion efficiency
- A long life core
- A reduced need for AC power

# *Design Tasks in the First Phase*

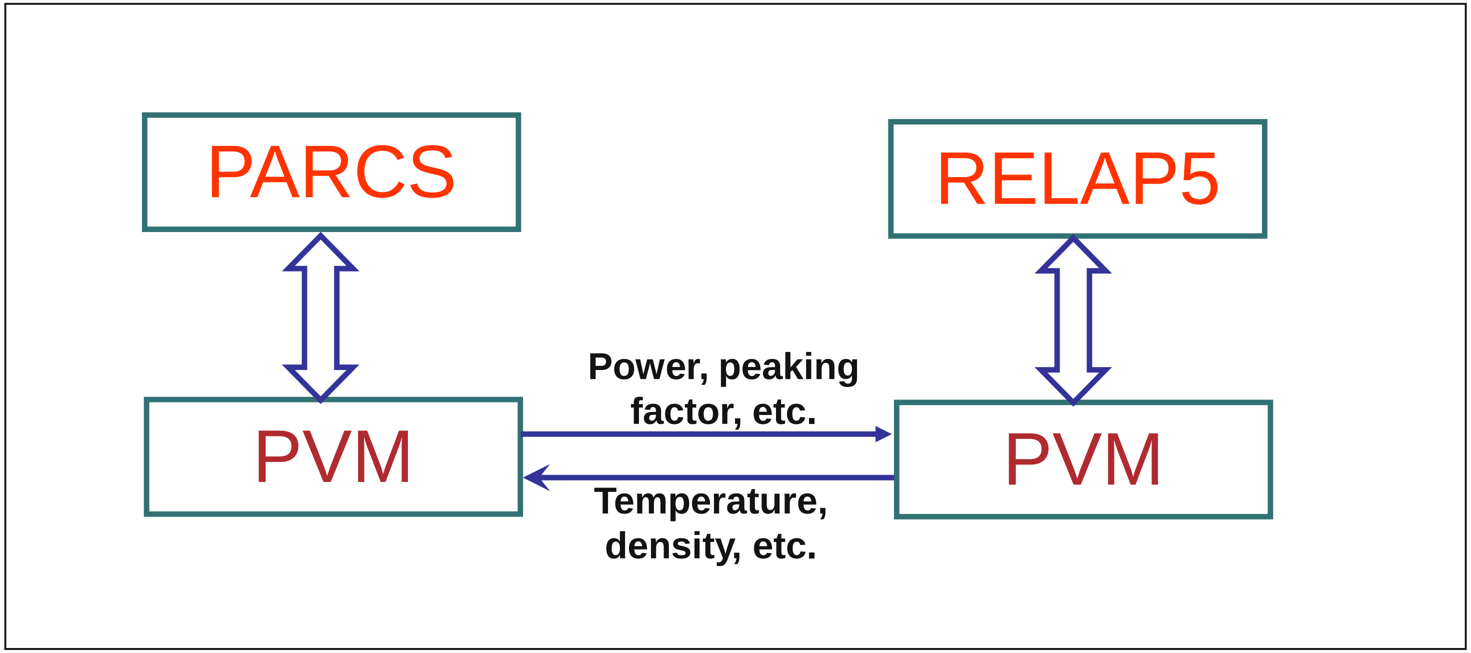
- Scaling analysis to determine the preliminary design parameters of the NMR-50
- Develop NMR-50 thermal hydraulics model to perform safety-state design study
- Modify the integral test facility by following the scaling analysis code modeling
- Develop neutronics and thermal hydraulics coupled core model for reactor analysis
- Perform comprehensive neutronics and fuel cycle study in conjunction with the core T/H design.

# Neutronics Design and Analysis Code System




**Ref.** Y. Xu and T. Downar, "GenPMAXS-V6: Code for Generating the PARCS Cross Section Interface File PMAXS", GenPMAXS manual, University of Michigan, March (2012)

# *Parallel Virtual Machine (PVM)*




The messages coupling PARCS/Relap5 are transferred via PVM.

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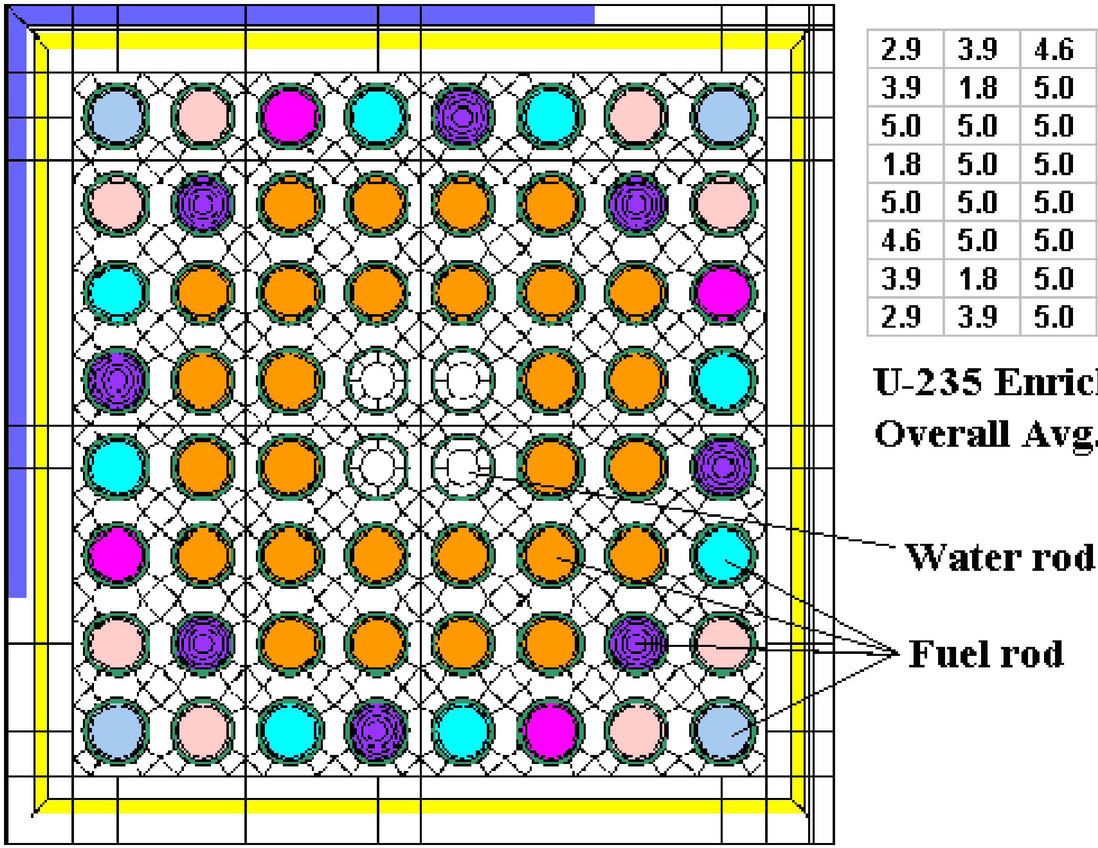
# Fuel Assembly Candidate One (GE 8x8, 8 Gd Rods)



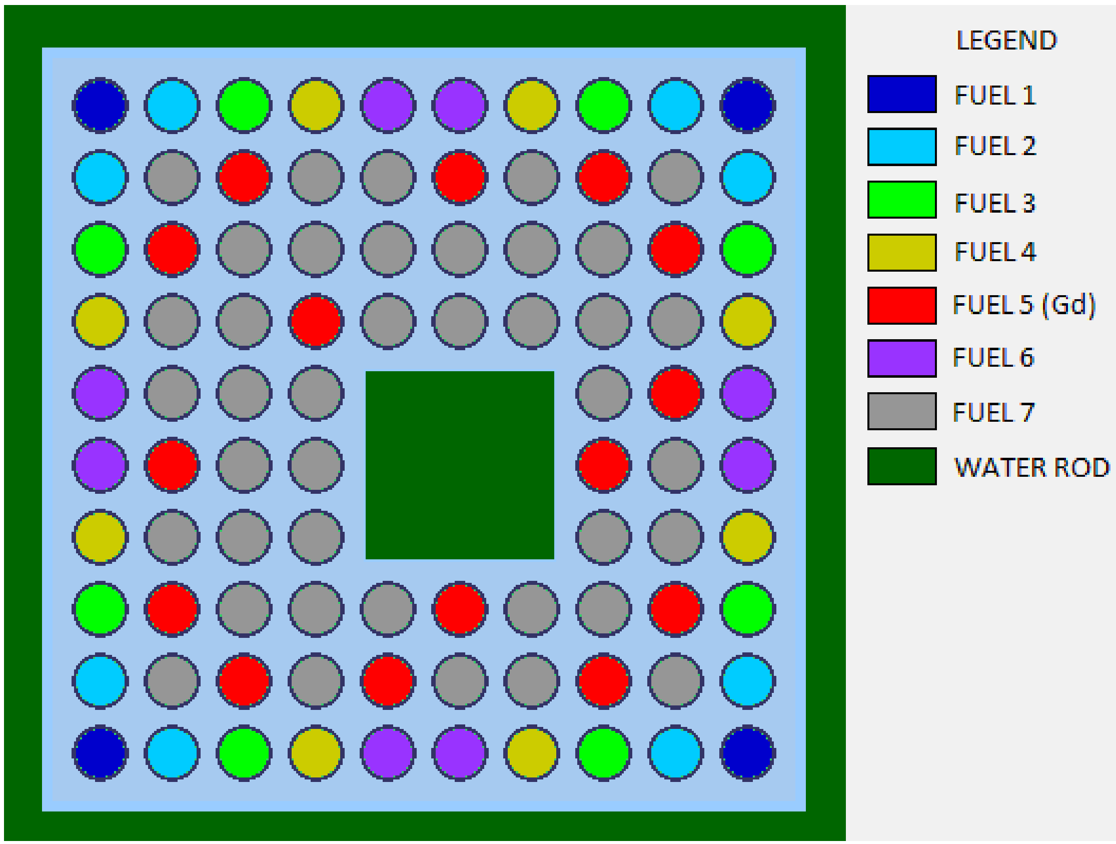

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2.9 | 3.9 | 4.6 | 5.0 | 1.8 | 5.0 | 3.9 | 2.9 |
| 3.9 | 1.8 | 5.0 | 5.0 | 5.0 | 5.0 | 1.8 | 3.9 |
| 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 4.6 |
| 1.8 | 5.0 | 5.0 | 0.0 | 0.0 | 5.0 | 5.0 | 5.0 |
| 5.0 | 5.0 | 5.0 | 0.0 | 0.0 | 5.0 | 5.0 | 1.8 |
| 4.6 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| 3.9 | 1.8 | 5.0 | 5.0 | 5.0 | 5.0 | 1.8 | 3.9 |
| 2.9 | 3.9 | 5.0 | 1.8 | 5.0 | 4.6 | 3.9 | 2.9 |

**U-235 Enrichment wt%**
**Overall Avg. at 4.26%**

# Fuel Cycle Length Study on GE Assembly

| CASE # | 1 | 2 |
|---|---|---|
| Average U-235 wt% | 4.26 | 5 |
| Cycle Burnup (MWd/KgU) | 30.46 | 36.91 |
| Fuel Cycle Length (Years) | 7.56 | 9.16 |
| Local Peaking Factor | 1.276 | 1.634 |
| k-inf at BOC | 1.04725 | 1.04831 |

# Fuel Assembly Candidate Two (AREVA Atrium-10B)




| Fuel Type | Enrichment (%) |
|---|---|
| 1 | 2.83 |
| 2 | 3.88 |
| 3 | 4.61 |
| 4 | 4.85 |
| 5 | 5.00/3.5 |
| 6 | 4.85 |
| 7 | 5.00 |

# Parameters Comparison between GE and AREVA Fuel Assembly

| Assembly Type | GE-BP-8 | Atrium-10B |
|---|---|---|
| Fuel rod array layout | 8 x 8 | 10 x 10 |
| Pitch of square rod array (mm) | 16.200 | 12.954 |
| Fuel rod outside diameter (mm) | 12.27 | 10.05 |
| Fuel rod cladding thickness (mm) | 0.8126 | 0.6058 |
| Pellet-to-cladding gap (mm) | 0.2032 | 0.0851 |
| Fuel density (g/cm3) | 10.475 | 10.450 |
| Gadolinium (Gd) rods U-235 wt% | 1.8 | 5 |
| Burnable poison | Gd | Gd |
| Number of fuel rods per assembly | 60 | 91 |
| Number of water rods per assembly | 4 | 9 |
| Fuel Assembly pitch (mm) | 155.0 | 152.4 |

**As an integral effect, the total fuel volume in AREVA assembly is raised by 2%.**

# Parametric Study Results of the AREVA Fuel Assembly

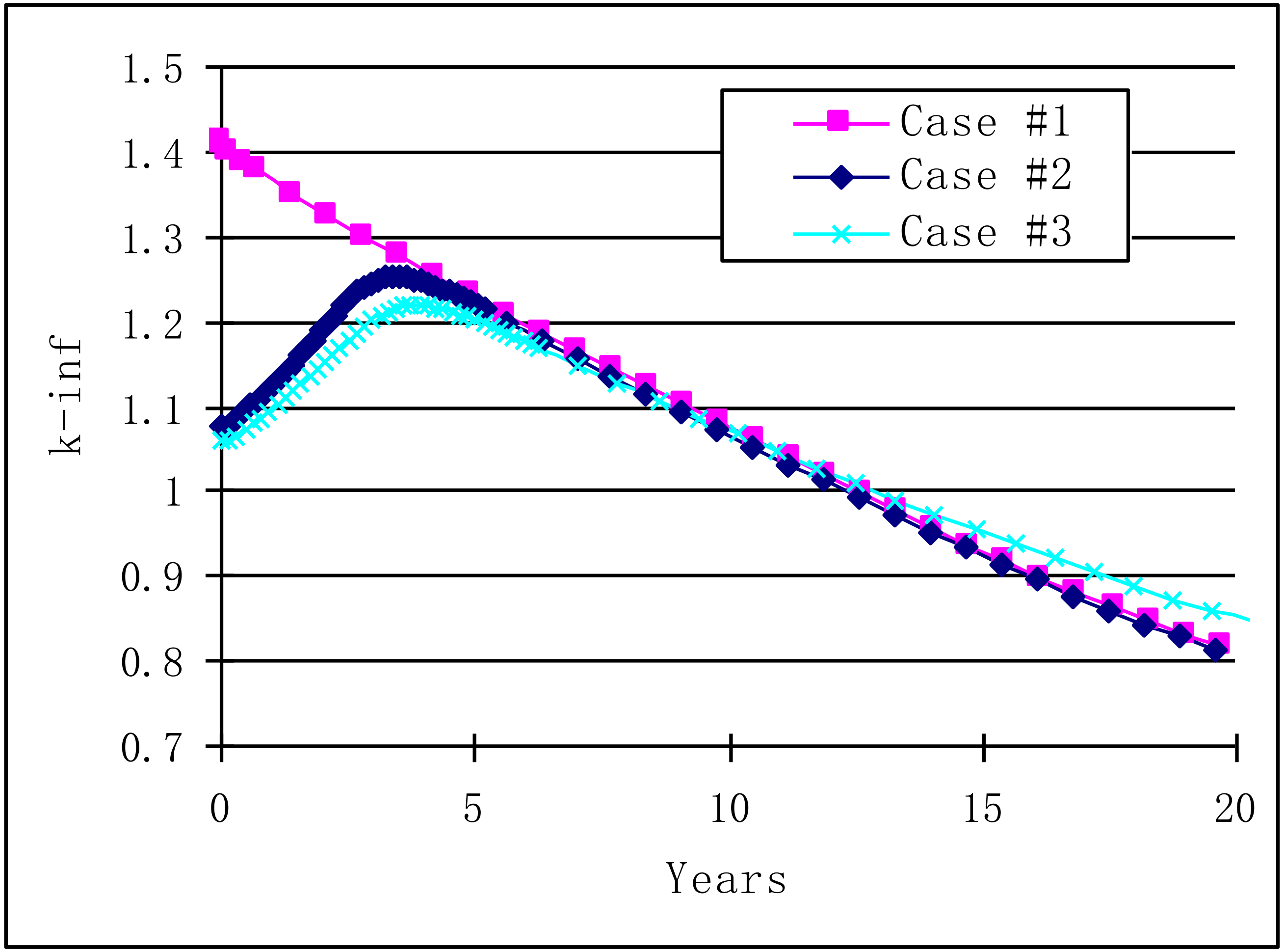
Fuel type and the assembly performance in three investigated cases.

| | Case #1 | Case #2 | Case #3 |
|---|---|---|---|
| 1 | 5.00 | 5.00 | 2.83 |
| 2 | 5.00 | 5.00 | 3.88 |
| 3 | 5.00 | 5.00 | 4.61 |
| 4 | 5.00 | 5.00 | 4.85 |
| 5 | 5.00/ 0.0[1] | 5.00/ 3.5 | 5.00/ 3.5 |
| 6 | 5.00 | 5.00 | 4.85 |
| 7 | 5.00 | 5.00 | 5.00 |

[1]Gd Fuel rod indicating both fissile enrichment and Gd weights of the fuel.

| CASE # | 1 | 2 | 3 |
|---|---|---|---|
| Avg. U-235 wt% | 5.00 | 5.00 | 4.75 |
| Gd wt% | 0.0 | 3.5 | 3.5 |
| Rod diameter (mm) | 10.05 | 10.05 | 10.55 |
| Water/UO2 ratio | 2.748 | 2.748 | 2.334 |
| Specific power (W/gU) | 9.74 | 9.81 | 8.76 |
| Cycle Burnup (GWd/T) | 37.345 | 36.720 | 33.395 |
| Cycle Length (Years) | 10.50 | 10.26 | 10.44 |
| Local Peaking Power | 1.458 | 1.741 | 1.268 |
| k-inf at BOC | 1.41262 | 1.07872 | 1.06059 |

# The k-inf Behavior In the Fuel Cycle Lifetime



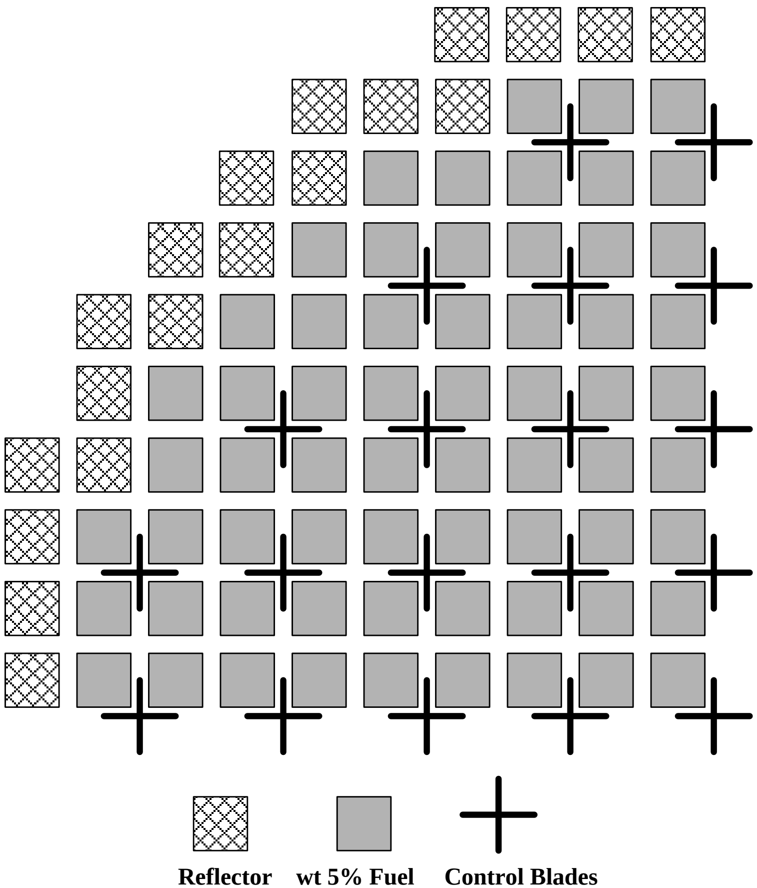
# *Thermal Restriction for the NMR-50 Core Design*

- Maximum fuel linear power density (MFLPD)
  - Characterize the limit of peak clad temperature during LOCA
- Minimum critical power ratio (MCPR)
  - Characterize the critical heat flux when the dryout phenomenon occurs in BWR

**Table. Reference Design Criterions from SBWR-600 and ESBWR**

| Reactor Type | SBWR-600 | ESBWR |
|---|---|---|
| MFLPD (kW/m) | 45.3 | 44.0 |
| Average linear power density (kW/m) | 16.6 | 15.1 |
| Total peaking factor | 2.73 | 2.91 |
| Design axial peaking factor | 1.45 | 1.50 |
| MCPR | 1.32 | 1.4-1.5 |

# Single Assembly Core Design for NMR-50




Radial view of quarter core configuration

NMR-50 Core design parameters
(Prepared for PARCS input)

| Core Property | NMR-50 |
|---|---|
| Assembly layout | 18 x 18 |
| Active fuel length (m) | 1.372 |
| Bottom reflector length (m) | 0.1524 |
| Top reflector length (m) | 0.1524 |
| Water rods (total) | 1024 |
| Number of fuel assemblies | 256 |
| Number of reflector assemblies | 19 |
| Control blades | 57 |

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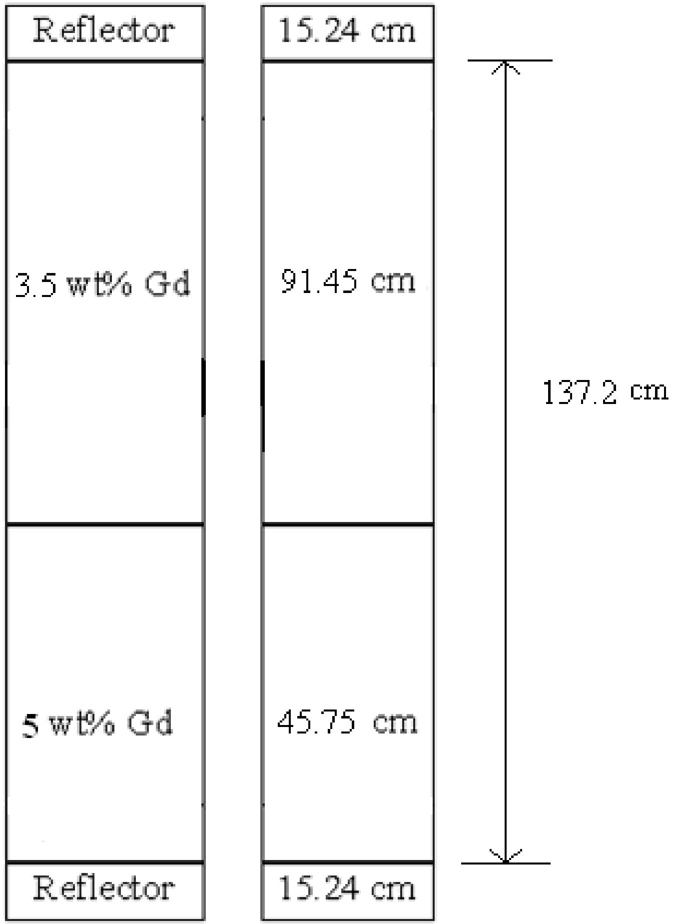
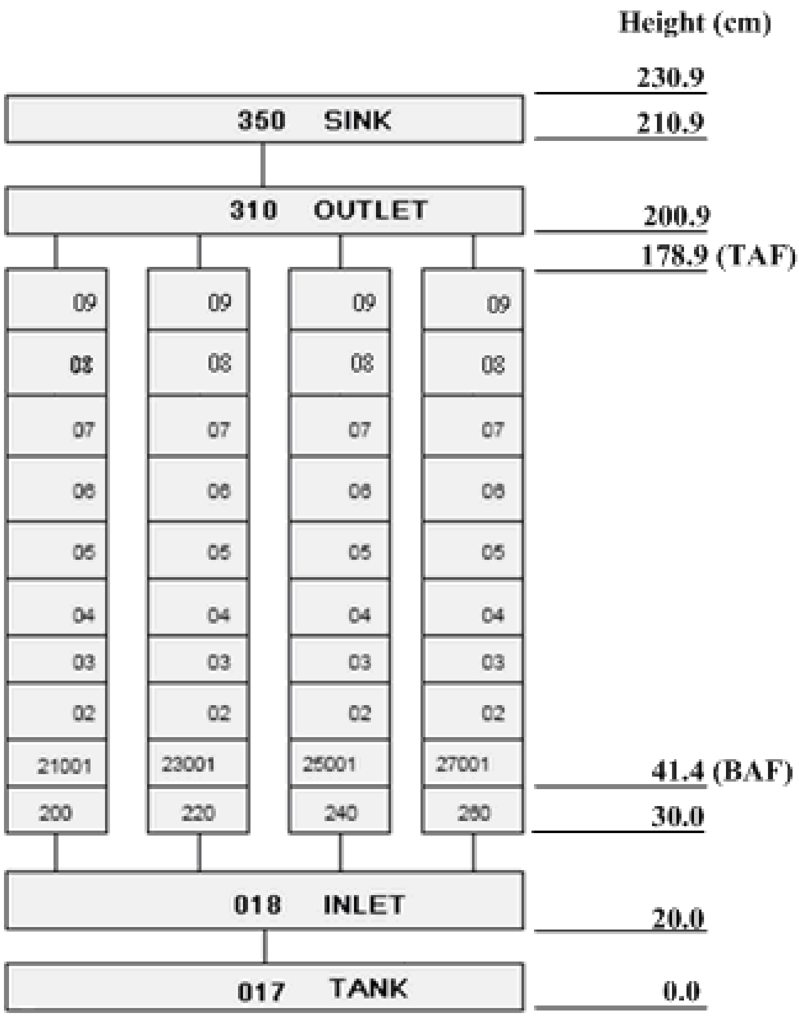
# Axial Zoning of the Gd Fuel Rods




- ✓ Different Gd wt% in axial zones to counteract the reactivity penalty resulted from void in the upper region
- ✓ Two graphite reflectors are placed on bottom and top segment of the fuel rod
- ✓ The active fuel length for the fuel rod is 137.2 cm

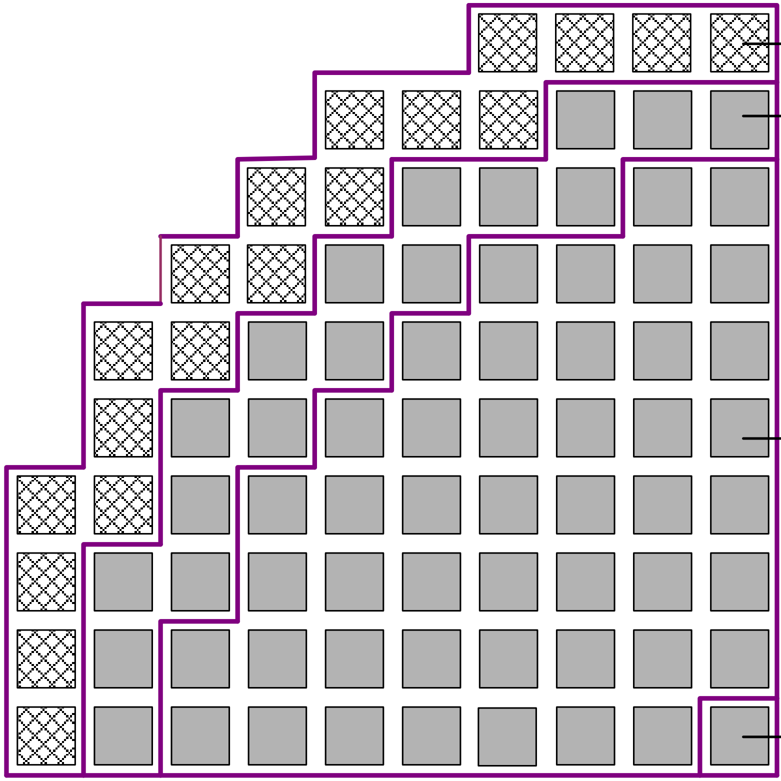
# Simplified T/H Model for NMR-50 Core




## Some T/H design parameters (Prepared for RELAP5 input)

| Core Property | NMR-50 |
|---|---|
| Designed thermal power (MWth) | 165 |
| Core coolant rate (kg/h) | $2.23 \times 10^6$ |
| Power density (kW/liter) | 20.75 |
| Core pressure (MPa) | 7.178 |
| Active fuel length (m) | 1.372 |
| Core average quality | 0.143 |
| Coolant saturation Temp. (°C) | 287.3 |
| Core Inlet Temp. (°C) | 278.5 |
| Total core flow area ($m^2$) | 4.013 |
| Core bypass flow area ($m^2$) | 1.763 |

# Radial Mapping of Neutronics and T/H Model

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| Relap5 Vol. | Channel type | # of Assemblies |
|---|---|---|
| 210 | Bypass channel (reflector) | 19 |
| 230 | Average channel | 46 |
| 250 | Peripheral channel | 17 |
| 270 | Hot channel | 1 |

# *Some Neutronics Results for <u>NMR-50</u> at BOC*

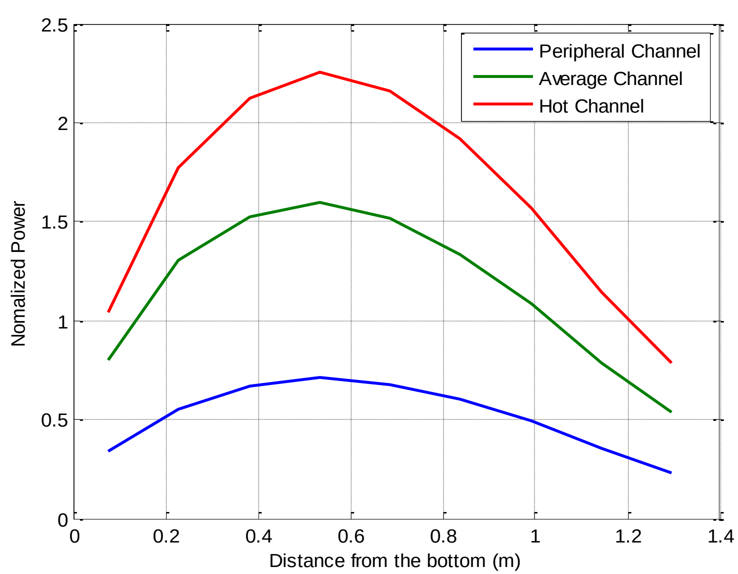
Initial CR Positions

| | | | | |
|---|---|---|---|---|
| | | | 0 | 0 |
| | | 0 | 0 | 0 |
| | 0 | 0 | 0 | 2192 |
| 0 | 0 | 0 | 2192 | 2392 |
| 0 | 0 | 2192 | 2392 | 2392 |

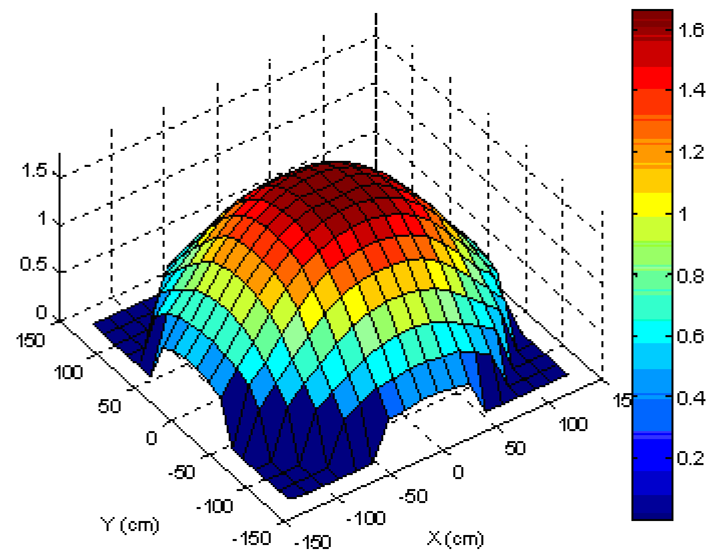
Final CR Positions

| | | | | |
|---|---|---|---|---|
| | | | 0 | 0 |
| | | 0 | 0 | 0 |
| | 0 | 0 | 0 | 229 |
| 0 | 0 | 0 | 229 | 249 |
| 0 | 0 | 229 | 249 | 270 |

Fig. Control rod insertion positions for criticality search at BOC. The notch value of a fully inserted control rod is 3192.




Axial power distribution for different flow channel



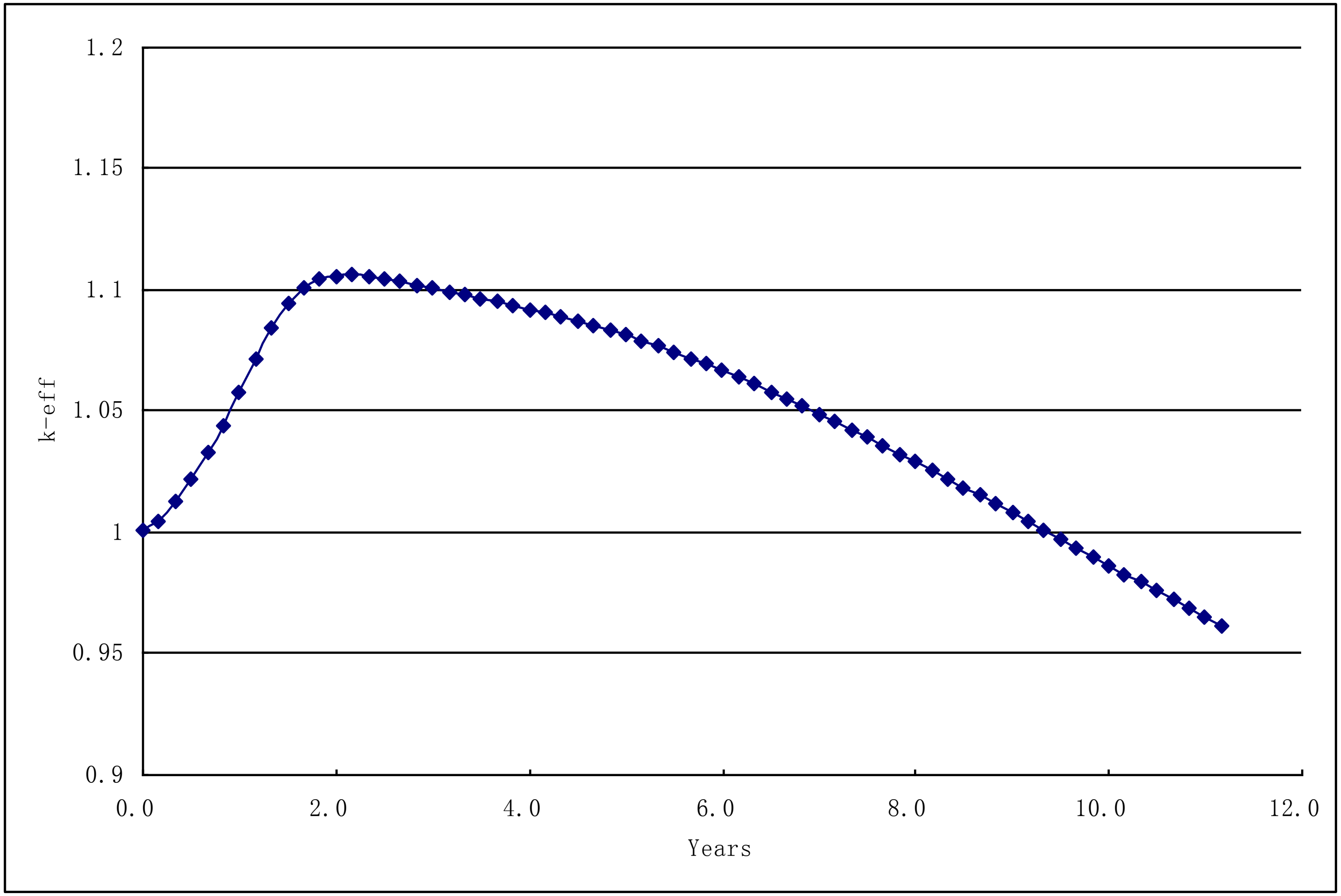

Radial power distribution

# The T/H Performance of the NMR50 at BOC

| | SBWR-600 [Ref.] | NMR-50 |
|---|---|---|
| MFLPD (kW/m) | 45.30 | 15.36 |
| Average LPD (kW/m) | 16.60 | 5.16 |
| Total peaking factor | 2.73 | 2.98 |
| MCPR (minimum) | 1.32 | 2.25 |

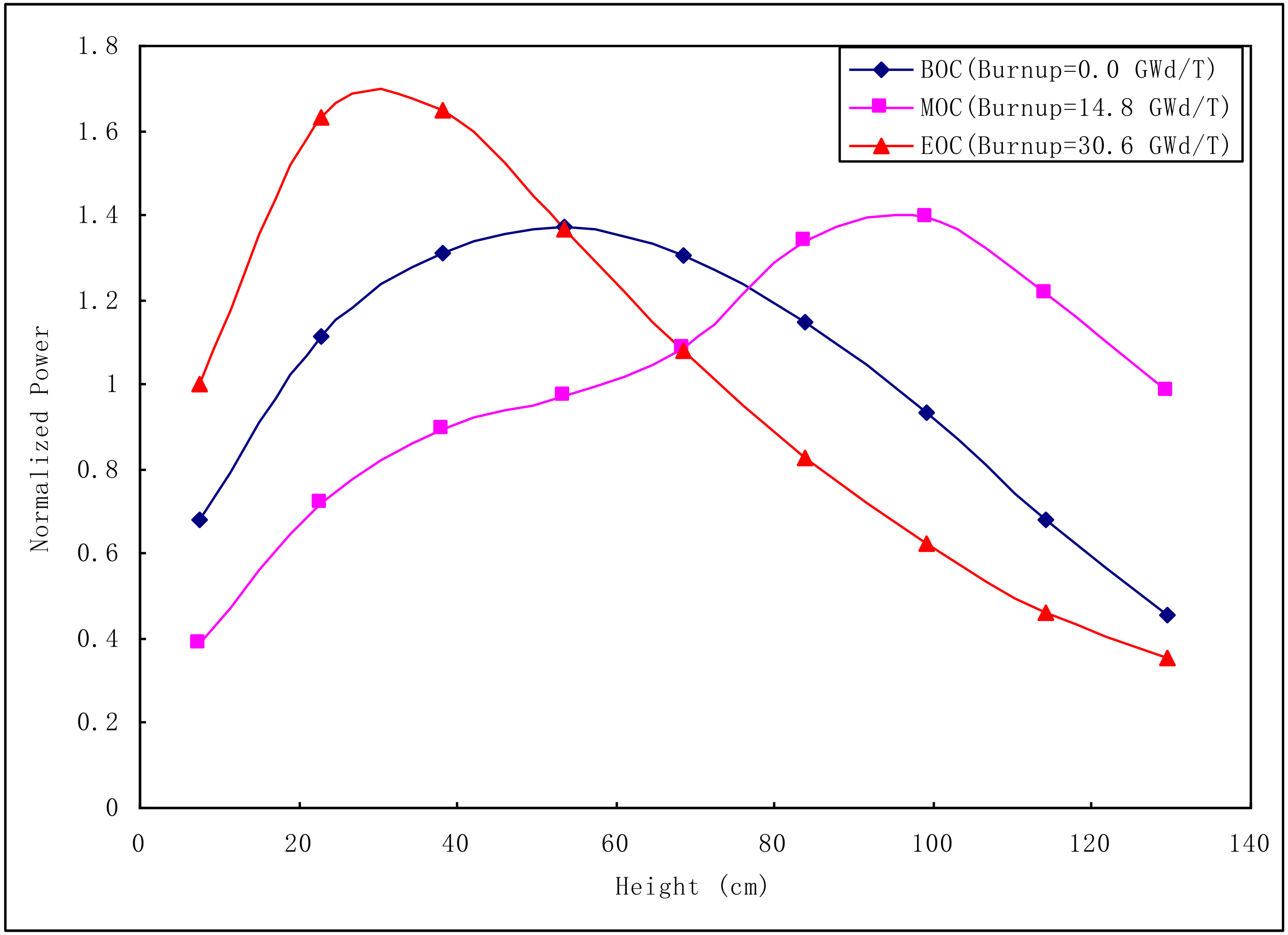
**Ref.** Simplified Boiling Water Reactor Standard Safety Analysis Report (SSAR)," General Electric, 25A5113 Rev. A, August, 1992.

# Results of Core Fuel Cycle Study

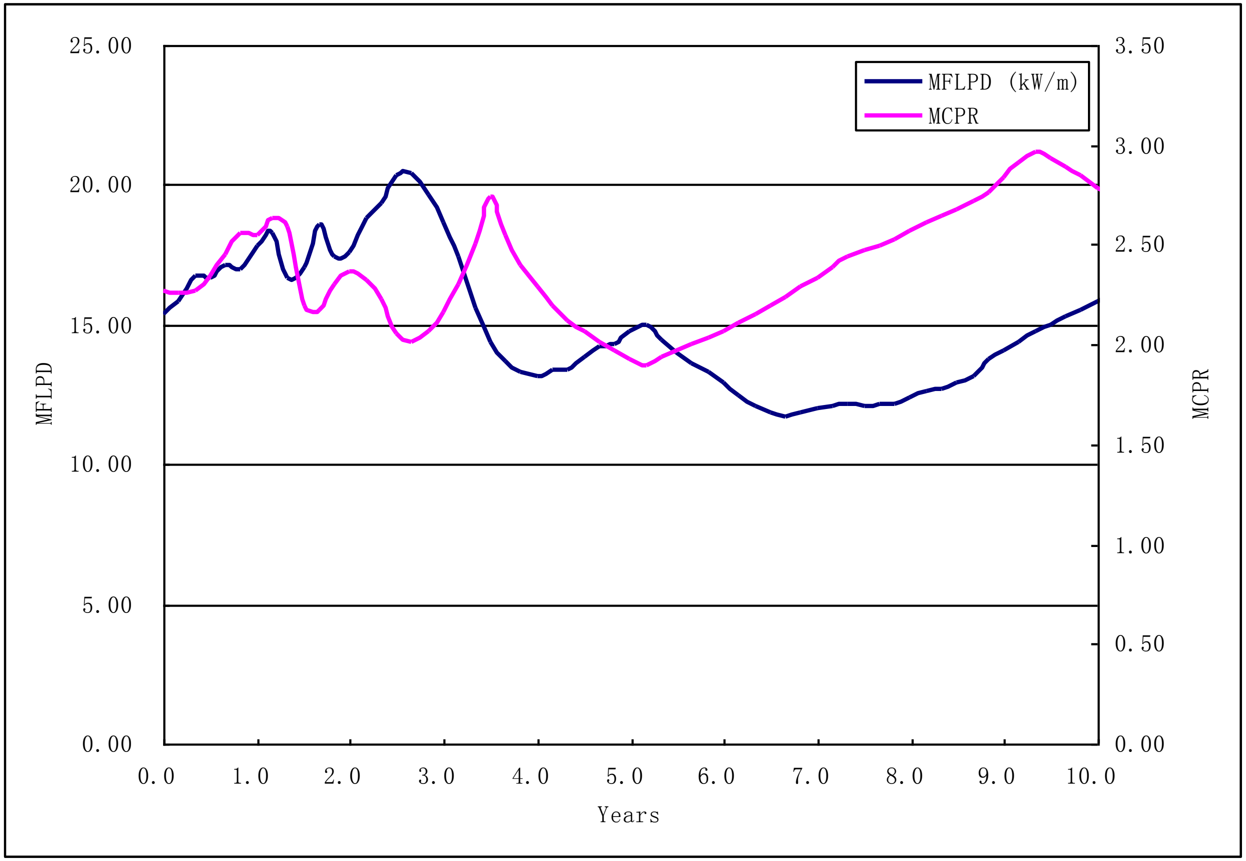



The k effective behavior along the full fuel cycle with control rods all out (RAO) condition.

# Axial Power Shape at BOC, MOC and EOC



# The Performance of the thermal Limit Parameters along with the fuel cycle




Recall the thermal restriction in SBWR-600:

MFLPD= 45.30 kW/m and MCPR=1.32.

# *Summary of the Talk*

- The neutronics and T/H coupled core design model for the NMR-50 based on CASMO, PARCS and RELAP5 code system is fully accomplished.
- Parametric study on fuel assemblies are carried out to select the optimized candidates to meet the design objective and constraints.
- The neutronics/TH coupled core simulation at both BOC and the full fuel cycle are preformed with the developed NMR-50 model and some performance results are delivered.
- The desired 10 years fuel cycle length has been achieved with the present design without the violation of the key thermal hydraulics performance criterions.